NASA-CR-204062

FINAL
7N-92-CR
025877

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Final Technical Report

Project Title: **Particle Growth and Agglomeration in the Solar Nebula**

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Duration of grant: 11/01/90 – 12/31/96

Award number: NASA Grant: NAGW-2243

Research Accomplished

The main focus of this study was the identification of particle-growth and agglomeration processes in the solar nebula evident in chondrite thin sections and hand samples. There are several fundamental but unresolved problems associated with the first stages of nebular accretion. These mechanical steps can be investigated petrographically and by numerical simulation. The ratio of fine, micrometer-size dust to chondrules shows large variations among chondrite groups; our petrographic and compositional studies helped define the processes that led to the incorporation of this fine matrix/rim dust into the chondrites. We formulated two hypotheses that led to different predictions: (1) matrix-like rims were accumulated as compact mantles around free-floating chondrules and matrix material was accreted to the chondrite parent bodies as a separate component, and (2) rims originally formed as fluffy, porous aggregates that collected and embedded chondrules and chondrule fragments, and it was only during asteroidal compaction that the presently observed rims formed.

Krot et al. (1997) reported that large numbers ($n \geq 100$) of pyroxene-rich microchondrules (≤ 40 μm in apparent diameter) occur together with irregularly shaped pyroxene-rich fragments and relatively rare ferroan olivine microchondrules within fine-grained rims around four low-FeO porphyritic olivine chondrules and one barred olivine chondrule in several type-3 ordinary chondrites: LL3.1 Bishunpur, L3.4 EET90161, L3.4 EET90261, LL3.4 Piancaldoli and LL3.0 Semarkona. Both types of microchondrules are embedded in high-FeO fine-grained matrix materials. They are typically accompanied by irregularly shaped pyroxene fragments that form a continuum win composition and shape with the low-FeO pyroxene microchondrules. The pyroxene-rich surfaces of the host chondrules project into the surrounding rims as peninsulas with rounded embayments, consistent with remelting. Although on average less ferroan, the peninsulas overlap the fragments and low-FeO microchondrules in composition and appear to have been the main source of these objects.

The occurrence of numerous low-FeO pyroxene-rich microchondrules with similar textures and compositions within high-FeO fine-grained matrix rims around normal-size chondrules and the apparent remelting of the surfaces of the host chondrules indicate that the microchondrules formed after solidification of the host chondrules mainly be remelting of their pyroxene-rich surfaces. The remnants of the pyroxene-rich rims are preserved as peninsulas extending outward from the chondrule surface and as irregularly shaped pyroxene fragments that coexist with the microchondrules. Because a newly formed microchondrule "cloud" would dissipate quickly due to random motions of the individual microchondrules, it seems inescapable that the fine-grained material, which now surrounds the microchondrules, was in their immediate vicinity when they formed and served as a trapping matrix. The rare high-FeO olivine microchondrules probably formed at the same time as the low-FeO pyroxene microchondrules by melting adjacent portions of the porous dust.

Wasson (1995a) pointed out that published SEM images of matrix lumps and matrix-like rims in type-3 chondrites show them to be relatively compact. Although some porosity is present (as evidenced by electron microprobe totals that have values <100 wt.%), it does not reach values comparable to those expected from low-velocity collisions in the solar nebula. It seems unlikely that this low porosity results from efficient packing of each grain as it accretes to the matrix-like rim around a chondrule; if the relative velocities are low, fluffy structures should result, and if the relative velocities are high, then rim erosion should occur. This scenario could be avoided if centimeter-to-meter-size fluffy structures formed in low-turbulence regions of the nebular midplane. During accretion of these larger objects, they experienced enough compaction to form tough, low-porosity chondrites. If no chondrules were in a region, matrix lumps formed; if chondrules were widely separated, matrix-like rims formed, and if chondrules were close to other chondrules, only small amounts of intervening matrix material filled the interstices between them.

A long-standing problem in meteorite research is the identification of specific parent bodies for meteorites. This goal has been achieved for planetary meteorites (i.e., lunar and martian meteorites), but has remained elusive for asteroidal samples. Although a consensus has been reached that HED samples come from the asteroid 4 Vesta, this conclusion is precipitous because the pallasites and IIIAB irons (which have the same O-isotopic composition as the HED meteorites) are certainly not from Vesta (otherwise it would have been disrupted) and the low fall rate of HED meteorites does not require that they be adjacent to a major escape channel in the asteroid belt. If the 3:1 resonance is the chief escape channel from the asteroid belt, then the three parent bodies of the ordinary chondrites must be located near 2.5 AU and that the ordinary chondrites and their siblings must constitute a large fraction of the S asteroids.

Strong evidence for aqueous alteration on the parent bodies of type-3 ordinary chondrites was presented by Wasson and Krot (1994a), Krot (1994) and Krot and Wasson (1993). They showed that associations of fayalite-silica in type-3 chondrites occur outside chondrules and appear to have formed as replacement products of primary phases. These results show that major amounts of aqueous activity occurred on asteroids and that phases that were previously ascribed to nebular formation conditions (e.g., fayalite, magnetite) are probably the result of parent body processes. They proposed that fayalite formed from silica and that this accounts for low Mg in associated olivine and that the Mg was sequestered inside the lattices of mafic minerals and was thus inaccessible.

In contrast, chromitic chondrules probably formed in the solar nebula. These chondrules were described by Krot et al. (1993) who discussed the range of volatility of Cr under proposed nebular conditions. They proposed that both Cr and Al became enriched in residues formed by incomplete evaporation of presolar lumps of material. The spinels remained as solid phases when the bulk of the silicates were incoporated into the evaporating melt. Vaporization of Al and Cr were inhibited by the slow kinetics of diffusion. Subsequent melting and crystallization of these residues fractionated Cr from Al; the resulting materials constituted the major components in the precursors of chromitic chondrules.

Igneous rims (a.k.a. coarse-grained rims) are partly melted rims that occur around chondrules and chondrule fragments in type-3 chondrites (e.g., Wasson and Krot, 1994b) . Their occurrence attests to remelting of chondrules in the solar nebula after rim acquisition, presumably by the same mechanism that formed chondrules in the first place. Compound chondrules probably formed in a similar way, by a multi-stage process involving the formation of a chondrule from pre-existing dust, acquisition of additional dust as a mantle and remelting of this dusty mantle at energies insufficient to melt the entire assemblage.

Recent astrophysical modeling has indicated that a substantial number of young pre-main-sequence stars undergo rapid heating episodes known as FU-Orionis-type events. It seems likely that our Sun also went through such a phase. If so, then planetesimals that existed in the inner asteroid belt would have been significantly heated numerous times by such events (Wasson, 1992).

References: recent publications funded by this grant

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